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For and on behalf of RWS Group Ltd
The 12th day of July 2004

Sol-gel polymer based on titanium oxide

The present invention relates to a polymer composition based on titanium oxide, to its use as a semiconductor element in a photovoltaic cell, and to a method for preparing it.

5 Photovoltaic cells convert solar energy into electricity by exploiting the photovoltaic effect that exists at the interface of a p-n junction between two semiconductors. Semiconductors based on silicon have been used, but the high cost of the raw material is not favorable to the industrial
10 development of such cells. Silicon has therefore been replaced with titanium oxide TiO_2 which is an inexpensive semiconductor and has stable photocatalytic properties. Its applications in the photovoltaic field are, however, limited, as it absorbs only within a narrow range of the solar
15 spectrum, owing to a wide bandgap. This range corresponds to the UV part and covers less than 10% of the entire solar spectrum. One solution consists in covering the surface of the titanium oxide with a photosensitizer in order to extend its photoactivity range into the region of the solar
20 spectrum. This technique has been employed using a ruthenium polypyridinic complex as photosensitizer (US-5 084 365) and it has allowed efficiencies of around 12% to be achieved. The cells containing, as semiconductor, titanium oxide activated by a photosensitizer have a production cost less than that of
25 the photovoltaic cells of the prior art. However, their operating lifetime, which is about 10 years, is considerably shorter than that of single-crystal silicon cells (which is around 20 years), and their efficiency is lower.

The inventors have now found that the performance of a
30 titanium oxide used as semiconductor in a photovoltaic cell can be optimized by controlling the microstructural or mesostructural scale of the morphology. The object of the present invention is therefore to provide a particular titanium oxide exhibiting improved performance when it is
35 used as semiconductor element in a photovoltaic cell.

The subject of the present invention is therefore a composition based on titanium oxide, a method for preparing

it and a photovoltaic cell that contains it as semiconductor element.

The composition according to the present invention is essentially formed by a polymer based on titanium oxide, which may be represented by the formula $\text{TiO}_x(\text{OH})_y(\text{H}_2\text{O})_z$ in which $x+y+z = 3$, in the form of a gel or in the form of a sol. It is characterized in that:

- the polymer has a structure of one-dimensional (1D) character and it consists of fibers wound concentrically with a periodicity, deduced from the space in between the fibers, of between 3.5 Å et 4 Å;
- each fiber is made up of TiO_6 octahedra;
- each TiO_6 octahedron shares two opposed edges with two adjacent octahedra (2×2.92 Å) in order to form infinite chains that grow along the axis of a fiber; and
- two adjacent chains form double strands by the commoning of edges (2×3.27 Å).

The one-dimensional structure of the $\text{TiO}_x(\text{OH})_y(\text{H}_2\text{O})_z$ polymer (denoted hereafter by TiO polymer) is detected by transmission electron microscopy. The chain structure is revealed by EXAFS analysis (Extended X-ray Absorption Fine Structure).

A polymer composition according to the invention (denoted hereafter by polymer TiO composition) may be translucent or be colored. The composition is translucent when it is shielded from the light and when the titanium is essentially in the Ti^{4+} form, the polymer then corresponding to the formula $\text{TiO}(\text{OH})_2$. When the titanium is essentially in the Ti^{3+} form in the TiO polymer, a broad absorption band exists in the visible range (between 400 and 850 nm), which results in a violet, blue, midnight blue or green coloration of the composition. The coloration changes with the proportion of Ti^{3+} . It goes from violet, in the case of low Ti^{3+} concentrations to green in the case of high concentrations. When all the titanium is in the Ti^{3+} form, the TiO polymer corresponds to the formula $\text{TiO}(\text{OH})(\text{H}_2\text{O})$.

A TiO polymer composition according to the invention may be obtained from TiOCl_2 . Since the TiOCl_2 compound is highly hydroscopic, it is used in the $\text{TiOCl}_2 \cdot y\text{HCl}$ form, i.e. in

solution, dissolved in concentrated hydrochloric acid. Advantageously, the concentrated HCL solution is an approximately 2M aqueous solution. The TiOCl_2 concentration in this solution is preferably between 4M and 5M.

5 According to a first embodiment, the TiO polymer composition according to the invention may be obtained in oxidized form, in which the titanium is in the Ti^{4+} oxidation state, by a method that consists in:

- preparing a TiOCl_2 solution in dimethylformamide (DMF)
10 by introducing $\text{TiOCl}_2 \cdot y\text{HCl}$ into DMF, in proportions such that the concentration (C_{Ti}) of Ti atoms is less than 2M;

- heating the solution thus obtained to a temperature between room temperature and 90°C ; and

- holding the solution at this temperature for a
15 certain time.

The temperature hold time which depends on the temperature. For example, when the solution is held at 65°C , a time of 24 h is sufficient.

The $\text{TiO}(\text{OH})_2$ polymer thus obtained may be converted into
20 its reduced form in which at least part of the titanium is in the Ti^{3+} oxidation state, by UV irradiation (for example at $\lambda = 360 \text{ nm}$) of the composition in an inert atmosphere, which induces a coloration (violet, blue or green, depending on the Ti^{3+} concentration), this coloration being maintained when
25 the irradiation ceases.

The TiO polymer composition is obtained in the form of a colloidal solution or sol in DMF when C_{Ti} is less than 1M and in the form of a gel when C_{Ti} is greater than 1M.

In a second embodiment, the TiO polymer composition of
30 the invention is obtained directly in reduced form, in which at least a part of the titanium is in the Ti^{3+} oxidation state by a method consisting in reducing TiOCl_2 using a species that is oxidizable at a potential of less than $-0,05 \text{ V}$ with respect to a standard hydrogen electrode. As an example,
35 mention may be made of metals in oxidation state zero, such as Ni, Fe, Al, Cr, Zr, Ti, Nb, Cs, Rb, Na, K, Li, La and Ce, ionic compounds, in which the cation is chosen from V^{2+} , Ti^{2+} and Cr^{2+} , and ionic compounds in which the anion is chosen from $\text{S}_2\text{O}_3^{2-}$, H^- , and S_2^{2-} . Zinc is particularly preferred. In

this case, the TiO polymer composition according to the invention is obtained with a coloration. If it is then irradiated by UV radiation, the content of Ti^{3+} species increases and its coloration changes from violet to blue and then to green as the content of Ti^{3+} ions increases.

A first variant of the method of preparation involving reduction by an oxidizable species, consists in preparing a $TiOCl_2$ solution in dimethylformamide (DMF) starting with $TiOCl_2 \cdot yHCl$, such that the concentration (C_{Ti}) of Ti atoms is less than 2M, in adding the oxidizable species, in heating the solution to a temperature between room temperature and 90°C and in holding the solution at this temperature for a certain time, which depends on the temperature.

A second variant of the method of preparation, involving reduction by an oxidizable species, consists in introducing the oxidizable species into a $TiOCl_2 \cdot yHCl$ solution in which C_{Ti} is less than 2M, and in maintaining the reaction mixture at a temperature between room temperature and 90°C.

In both variants, it is preferred to introduce the metal in the form of chips. The ionic compound may be introduced in the form of powder, liquid or gas.

When a composition according to the invention is prepared by a method using DMF, it contains dimethylammonium chloride and formic acid. These constituents may be detected for example by proton (1H) NMR analysis, which also makes it possible to determine the quantity thereof. When the C_{Ti} concentration in the initial reaction mixture is less than 1M, the composition is a colloidal solution of uncrosslinked polymer in DMF. When the initial concentration C_{Ti} is greater than 1M, the polymer is crosslinked and the composition is in gel form.

When a composition according to the invention is prepared according to the second variant of the method involving reduction by an oxidizable species, i.e. in the absence of DMF, said composition is a colloidal solution of uncrosslinked polymer in water when C_{Ti} is less than 1M. When C_{Ti} is greater than 1M, the polymer is crosslinked and the composition is in gel form.

Whatever the method used to obtain the reduced form of the polymer exhibiting coloration, the oxidized form may be obtained by subjecting the polymer composition to oxidation in air so that it resumes its translucent appearance.

5 A TiO polymer composition according to the invention is photochromic in character. When it is obtained in gel form, it may advantageously be used in a photovoltaic cell in which the active material of the photoanode is the composition containing the Ti^{3+} reduced form, and the active material of
10 the photocathode is a composition containing the Ti^{4+} oxidized form.

A composition of the invention may furthermore be used for the production of solar protection glazing. A glass pane covered with a composition of the invention in the form of a
15 gel remains translucent when it is away from sunlight. Under the effect of irradiation by visible light, the glass pane assumes a midnight blue coloration. This phenomenon can be made reversible by applying a potential allowing oxidation.

The present invention will be described in greater
20 detail by the following examples, which are given for illustration, but the invention is not, however, limited thereto.

Example 1

10 ml of DMF at 4 ml of a 4.3M $TiOCl_2$ solution in 2M
25 hydrochloric acid were introduced into a test tube, under an inert atmosphere of N_2 . After having closed the tube, it was placed in an oven at $65^\circ C$ and maintained at this temperature for 24 hours. It was then left to cool down and the appearance of a transparent gel was observed at room
30 temperature.

The presence of dimethylammonium chloride and formic acid was detected by 1H and ^{13}C NMR by IR and by Raman.

After having been exposed to visible light, the gel had an intense blue coloration, as a result of the reduction of
35 Ti^{4+} to Ti^{3+} . This phenomenon is reversible, and by opening the tube an oxidation takes place in the presence of the oxygen from the air, the gel again becoming transparent after a few minutes.

High-resolution imaging, obtained by transmission electron microscopy, showed that the structure of the $\text{TiO}(\text{OH})_2$ polymer obtained was of 1-dimensional (1D) character. The fibers of the polymer were wound concentrically in the manner of a cotton bol. The presence of substantial disorder in the direction perpendicular to the stack of fibers was manifested in the diffraction pattern by the presence of diffuse lenticular spots. The periodicity, deduced from the spacing between the fibers, was estimated to be 3.5 - 4 Å.

Example 2

The operating method described in example 1 was repeated, for several preparations, varying only the concentration C_{Ti} in the test tube. Each test tube, filled with air or N_2 was subjected to a heat treatment similar to that of example 1.

The formation of a gel was observed only for C_{Ti} concentrations between 1M and 2M. For concentrations where $C_{\text{Ti}} < 1\text{M}$, the mixture remained liquid and consisted of a colloidal solution of the polymer. For concentrations where $C_{\text{Ti}} > 2\text{M}$, an opaque white product forms that contains a transparent polymeric phase and an amorphous white precipitate, or a white precipitate of anatase in the case of very high concentrations.

Example 3

The optical properties of various specimens were measured for various irradiation states. For this purpose, four specimens were prepared, in air or in nitrogen, from a TiOCl_2 solution identical to that used in example 1:

No.	C_{Ti} (mol/l)	Vol. of TiOCl_2	Vol. of DMF	O_2	N_2
1	1.6M	1.3 ml	2.15 ml	X	
2	1.6M	1.3 ml	2.15 ml		X
3	1.45M	1.1 ml	2.15 ml	X	
4	1.45M	1.1 ml	2.15 ml		X

In a first series of tests, a fraction of each of solutions 1 to 4 was subjected to UV irradiation ($\lambda = 360$ nm) for 180 hours.

In a second series of tests, a fraction of each of solutions 1 to 4 was subjected to a heat treatment at 65°C for 15 hours, after which each fraction was subjected to UV irradiation ($\lambda = 360$ nm) for 180 hours.

Figures 1 to 4 show the optical absorption spectra of the solutions after various treatments. The absorption A, in arbitrary units, is plotted on the Y-axis. The wavelength λ , in nanometers, is plotted on the X-axis. In each of the figures, the solution spectra are indicated by the following symbols:

Solution 1	Solution 2	Solution 3	Solution 4
•	▲	○	Δ

Figure 1 shows the optical absorption spectrum of the untreated fraction of each of solutions 1 to 4. The four spectra are almost identical and show that there is no absorption in the visible range and that the influence of both the concentration and the conditioning atmosphere is negligible.

Figure 2 shows the optical absorption spectrum of the fraction of each of solutions 1 to 4 subjected to UV irradiation for 180 hours. The spectra indicate the presence of a strong absorption, which extends over a wide range in the visible, and also a slight shift of the absorption edge toward shorter wavelengths.

Figure 3 shows the optical absorption spectrum of the fraction of each of solutions 1 to 4 subjected to heating at 65°C for 15 hours. The spectra indicate a slight shift of the absorption edge toward shorter wavelengths relative to the spectra of the initial, untreated solutions.

Figure 4 shows the optical absorption spectrum of the fraction of each of solutions 1 to 4 subjected to heating at 65°C for 15 hours followed by UV irradiation for 15 hours. The spectra indicate a broad absorption band in the visible range. The absorption is greater in the case of the gel and

its maximum is shifted toward longer wavelengths than in the case of the corresponding initial solutions.

The structure of the $\text{TiO}(\text{OH})_2$ polymer gel was characterized by titanium K-edge EXAFS analysis. The results of the fine structure analysis give the number N of neighboring atoms, the distance R between an absorbent atom and its neighbors, the Debye-Waller factor σ , the energy shift ΔE_0 and the residue ρ . The results are given in the table below.

$\text{TiO}(\text{OH})_2$	N	$R (\text{\AA})$	$\sigma \times 10^2 (\text{\AA})$	$\Delta E_0 (\text{eV})$	$\rho (\%)$
Ti - O	3.91	1.89	1.3	0.48	
Ti - O	2.08	1.98	2.8	0.00	2.32
Ti - Ti	2.28	2.92	6.3	2.84	
Ti - Ti	1.1	3.27	1.7	6.85	

The idealized structure of the $\text{TiO}(\text{OH})_2$ polymer ribbon, which has a 1D character, is shown in figure 5 (B). It is similar to the structure observed in the case of hollandite. Each TiO_6 octahedron shares two opposed edges with two adjacent octahedra (2.92 \AA) in order to form infinite chains that run along the axis of the fiber. Two adjacent chains form double strands by commoning edges ($2 \times 3.27 \text{\AA}$). Because of the difference between the actual number of neighbors and the ideal value of 2, the polymer obtained may be crosslinked, as shown in figure 5(A).

Example 4

Four starting solutions were prepared by introducing a TiOCl_2 solution in concentrated HCl into DMF, in an amount such that the C_{Ti} concentrations were 0.03M, 0.04M, 0.05M and 0.06M respectively. 100mg of zinc chips were added to 3 ml of each of these solutions.

The change in coloration was monitored over time by measuring the absorption of the specimens using a Cary UV-Vis-NIR absorption spectrometer between 300 and 1200 nm. The absorption spectra are shown in figures 6 and 7. The absorption Abs. is plotted on the Y-axis (in arbitrary units). The wavelength λ is plotted on the X-axis (in nm). The spectra show that, between $t = 0 \text{ min}$ and $t = 500 \text{ min}$

(figure 6), an absorption peak is formed at 550 nm, which increases over time and is accompanied by three shoulders, at 630 nm, at 740 nm and at about 900 nm. After 500 min (figure 7), this peak tends to disappear and leaves instead a broad
5 absorption band lying between 630 and 740 nm. After 3150 min, i.e. more than 2 days, there is substantial absorption whatever the wavelength in the visible range. However, two peaks appear at 550 nm and 710 nm.